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Monopoles and hadron spectrum in quenched QCD

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Abstract

We study quenched hadron spectra with Wilson fermion in abelian gauge fields extracted by maximal abelian projection and in fields induced by monopoles on $16^3\times 32$ and $12^3\times 24$ lattices. Pion mass squared and quark mass defined through the axial Ward identity satisfy the PCAC relation. Gross features of the light hadron spectra are almost similar to those in $SU(3)$ gauge fields if normalization is made by the square root of the string tension. It is also shown that no sizable dynamical mass generation is found in the present range of κ when the monopole degree of freedom is removed from the abelian fields or from the $SU(3)$ gauge fields.

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I. INTRODUCTION

Understanding of color confinement is still an important subject of nonperturbative dynamics of quantum chromodynamics(QCD). Investigations along monopole condensation proposed by t'Hooft [1] have been developed especially in lattice Monte-Carlo simulations [2–12]. In the scenario, monopoles in abelian projected gauge field play a role of electrons in the superconductor. Color confinement is caused if the monopoles are condensed [1]. Such a scenario is well confirmed in lattice compact QED [13–18].

A key quantity of confinement, i.e. the string tension between quark and antiquark, has been measured and analyzed along this scenario. After the abelian projection in the maximal abelian (MA) gauge, the string tension derived from abelian Wilson loops gives almost the same value as that of $SU(2)$ [2,19]. Moreover, the monopole contribution to the abelian Wilson loops alone reproduces the string tension in $T = 0$ [7] and $T \neq 0$ [9] $SU(2)$ QCD.

The Polyakov loop is an order parameter of finite-temperature deconfinement transition in pure lattice gauge theory. It is shown that abelian Polyakov loops written in terms of abelian link fields alone play also a role of an order parameter [20,21] in $T \neq 0$ $SU(2)$ and $SU(3)$ lattice QCD simulations. Furthermore, an abelian Polyakov loop operator can be expressed by a product of contributions from the Dirac string of monopoles and from photons [22]. Only the former part of the abliean Polyakov loop reveals the confinement-deconfinement transition. These results are seen also in some unitary gauge fixings. These results strongly support that the 'tHooft conjecture [1] is realized in QCD.

What happens when quarks are introduced and what determines the hadron spectrum? Quarks and gluons are confined inside hadrons. Abelian dominance hypothesis claims that long wave dynamics of QCD is well projected on the abelian part of gauge fields after abelian projection. Then mass generation of light hadrons from scale invariant QCD is expected to be explained by the abelian and the monopole parts alone.

The expectation has been tested in the simulations in quenched $SU(2)$ QCD with Kogut-Susskind fermions [23]. It has been shown that light pion mode exists in the abelian and the monopole gauge fields. Its mass vanishes in the chiral limit while the mass of ρ meson remains finite as shown in $SU(2)$ gauge field. On the other hand, the propagators behave as a product of free staggered fermions in the photon part.

The purpose of this paper is to report new results of hadron spectra in the abelian gauge fields and the monopole gauge fields in quenched $SU(3)$ QCD with Wilson fermions.

In Section II we briefly review the maximally abelian gauge in lattice $SU(3)$ QCD and abelian gauge fields from the Dirac string of monopoles and photons. Our results are shown in Section III. We calculate hadron spectra and the quark mass from the axial Ward identity. The PCAC relation is shown to be satisfied. Finally we examine light hadron spectra in $SU(3)$ gauge field from which monopoles are removed. The pion and the ρ meson masses are degenerate irrespective of κ. The behavior is similar to those in the free field. Summary and remarks are given in Section IV.

II. DEFINITION

A. Maximally abelian (MA) gauge in $SU(3)$ QCD

We adopt usual $SU(3)$ Wilson action for gauge fields. The MA gauge is given by performing a gauge transformation $\widetilde{U}(s,\mu) = V(s)U(s,\mu)V^{-1}(s+\hat{\mu})$ such that

$$R = \sum_{s,\mu} (|\widetilde{U}_{11}(s,\mu)|^2 + |\widetilde{U}_{22}(s,\mu)|^2 + |\widetilde{U}_{33}(s,\mu)|^2) \tag{1}$$

is maximized. Then a matrix

$$X(s) = \sum_{\mu,a} [\widetilde{U}(s,\mu)\Lambda_a \widetilde{U}^\dagger(s,\mu) + \widetilde{U}^\dagger(s-\hat{\mu},\mu)\Lambda_a \widetilde{U}(s-\hat{\mu},\mu), \Lambda_a] \tag{2}$$

is diagonalized at all sites on the lattice. Here

$$\Lambda_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \Lambda_2 = \begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}, \Lambda_3 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix}. \tag{3}$$

After the gauge fixing is over, we can extract an abelian link field [24]

$$\widetilde{U}(s,\mu) = C(s,\mu)u(s,\mu), \tag{4}$$

where

$$u(s,\mu) = \mathrm{diag}(e^{i\theta^{(1)}(s,\mu)}, e^{i\theta^{(2)}(s,\mu)}, e^{i\theta^{(3)}(s,\mu)}) \tag{5}$$

$$\theta^{(i)}(s,\mu) = \arg(\widetilde{U}_{ii}(s,\mu)) - \frac{1}{3}\phi(s,\mu) \tag{6}$$

$$\phi(s,\mu) = \left[\sum_i \arg(\widetilde{U}_{ii}(s,\mu))\right]_{\mathrm{mod}\ 2\pi} \in [-\pi,\pi). \tag{7}$$

$u(s,\mu)$ is a diagonal abelian gauge field and $C(s,\mu)$ is a charged matter field.

B. Abelian gauge fields from the Dirac string and photon

A plaquette variable is given by $f^{(i)}_{\mu\nu}(s) = \partial_\mu \theta^{(i)}_\nu(s) - \partial_\nu \theta^{(i)}_\mu(s)$. Hence

$$\theta^{(i)}_\mu(s) = -\sum_{s'} D(s-s')[\partial'_\nu f^{(i)}_{\nu\mu}(s') + \partial_\mu(\partial'_\nu \theta^{(i)}_\nu(s'))], \tag{8}$$

where $D(s-s')$ is the lattice Coulomb propagator. If we fix the remaining $U(1)$ gauge degree of freedom in the Landau gauge, the abelian gauge fields are given by

$$\theta^{(i)}_\mu(s) = -\sum_{s'} D(s-s')\partial'_\nu f^{(i)}_{\nu\mu}(s'). \tag{9}$$

Extract the Dirac string from the field strength, satisfying $\sum_i k^{(i)}_\mu = \sum_i (1/2)\epsilon_{\mu\nu\rho\sigma}\partial_\nu n^{(i)}_{\rho\sigma} = 0$ [25]:

$$f_{\mu\nu}^{(i)}(s) = \bar{f}_{\mu\nu}^{(i)}(s) + 2\pi n_{\mu\nu}^{(i)}(s), \quad \begin{cases} -\pi < \bar{f}_{\mu\nu}^{(i)}(s) \leq \pi, \\ n_{\mu\nu}^{(i)}(s) = 0, \pm 1, \pm 2, \pm 3. \end{cases} \tag{10}$$

The abelian gauge field from the Dirac string is [22]

$$\theta_\mu^{Ds(i)}(s) = -2\pi \sum_{s'} D(s-s')\partial'_\nu n_{\nu\mu}^{(i)}(s'), \tag{11}$$

whereas the abelian gauge field from the photon is

$$\theta_\mu^{Ph(i)}(s) = -\sum_{s'} D(s-s')\partial'_\nu \bar{f}_{\nu\mu}^{(i)}(s'). \tag{12}$$

Abelian link fields from the Dirac string and from the photon are constructed as

$$u^{Ds}(s,\mu) = \mathrm{diag}(e^{i\theta_\mu^{Ds(1)}(s)}, e^{i\theta_\mu^{Ds(2)}(s)}, e^{i\theta_\mu^{Ds(3)}(s)}), \tag{13}$$

$$u^{Ph}(s,\mu) = \mathrm{diag}(e^{i\theta_\mu^{Ph(1)}(s)}, e^{i\theta_\mu^{Ph(2)}(s)}, e^{i\theta_\mu^{Ph(3)}(s)}). \tag{14}$$

III. SIMULATIONS AND RESULTS

Now let us evaluate the inverse of the Wilson fermion matrix

$$1 - \kappa \sum_\mu [(1-\gamma_\mu)U(s,\mu)\delta_{s+\hat{\mu},s'} + (1+\gamma_\mu)U^\dagger(s-\hat{\mu},\mu)\delta_{s-\hat{\mu},s'}] \tag{15}$$

for

- $U(s,\mu)$ $(SU(3))$,
- $u(s,\mu)$ (abelian),
- $u^{Ds}(s,\mu)$ (Dirac string),
- $u^{Ph}(s,\mu)$ (photon),
- $C(s,\mu)u^{Ds}(s,\mu)$ ((matter) $\times$ (monopole))
- $C(s,\mu)u^{Ph}(s,\mu)$ ((matter) $\times$ (photon))

and measure hadron mass spectra. κ is the hopping parameter. $C(s,\mu)u^{Ds}(s,\mu)$ $(C(s,\mu)u^{Ph}(s,\mu))$ corresponds to a link variable in which the photon part (the monopole part) is excluded from the $SU(3)$ link variable.

A. Simulations

Our calculations were done on 4PE, 8PE and 16PE systems of a vector parallel supercomputer Fujitsu VPP500. The simulations were performed as follows:

- Lattice sizes and lattice spacings adopted are listed in Table I.
- Antiperiodic (Periodic) boundary conditions in the time (space) direction.
- Number of sweeps for thermalization is $3000 \sim 8000$. Number of sweeps to get independent configurations is $1000 \sim 1200$. Number of configurations for average is listed in Table I.
- The criterion of the MA gauge condition is $\sum_s |\text{off diagonal part of } X(s)| < 10^{-7}$ where X is the operator to be diagonalized (Eq.(2)). An over-relaxation method is used.
- The criterion of the solution of the Wilson matrix inversion is $|\text{residue}| < 10^{-5}$. The hopping parameter expansion and the CG method with red-black preconditioning are used.
- The mass fitting function is

$$G(t) = c \cosh(m(t - N_t/2)). \tag{16}$$

Examples of hadron propagators in the abelian and the monopole gauge fields are shown in Fig.1 and Fig.2. Examples of κ adopted, the estimated masses of quark, π, ρ, proton(p) and Δ are listed in Table II.

B. The chiral limit

Let us evaluate the chiral limit. It has been known that the quenched approximation has a problem of chiral logs [26]. However, the linear relation between squared pion mass and quark mass holds for not very small quark mass [27]. We examine the relations in the abelian and in the monopole gauge fields as well as in $SU(3)$ gauge field.

Usually the chiral limit is given by demanding vanishing of the pion mass. It is derived by the following fit:

$$m_\pi^2(\kappa) = A_1(1/2\kappa - 1/2\kappa_c), \tag{17}$$

where κ_c is given by $m_\pi^2(\kappa_c) = 0$. This method is valid when we can regard $(1/2\kappa - 1/2\kappa_c) \sim m_q$. Quenched chiral perturbative theory predicts

$$m_q^{\overline{\text{MS}}} = Z_m(1/2\kappa - 1/2\kappa_c), \tag{18}$$

and it holds good in the usual lattice simulation with $SU(3)$ gauge fields.

Howeve in the abelian and the monopole gauge fields, the κ dependences of hadron and quark masses are not known. First, we use three types of fits for the pion mass; i.e., the fit (17) and

$$m(\kappa) = B_0 + B_1(1/\kappa), \tag{19}$$
$$m(\kappa) = C_0 + C_1(1/\kappa) + C_2(1/\kappa)^2. \tag{20}$$

The latter two types of the fits are used also for ρ, p and Δ. The critical hopping parameter κ_c is obtained by the condition $m_\pi(\kappa_c) = 0$. The masses of π, ρ, p and Δ are plotted versus $1/\kappa$ in Fig. 3 for the abelian background and Fig. 4 for the monopole one. We find a strange dependence of the hadron masses on κ. In the figures, a long dashed line, a solid line and a dashed line denote the fits (17), (19) and (20), respectively. For reference, we have plotted the masses at the chiral limit given by the average of the fits (19) and (20) at the most left side (κ_c is also given by the average) of Fig. 3 and Fig. 4. The error of the hadron masses at the chiral limit is estimated by the summation of the systematic error from the indefiniteness of the fitting functions and the statistical error given by the χ^2 fit. Unfortunately, these fittings have large ambiguities with respect to the masses at the chiral limit. The $\chi^2/d.o.f.$ are very large. We need, hence, another fit to extrapolate the hadron masses toward the chiral limit without using κ dependence.

We can define the quark mass from the axial Ward identity as follows [28]:

$$\frac{Z_P}{Z_A} m_q = -\lim_{t\to\infty} m_\pi \frac{\langle 0|A_4(t)P(0)|0\rangle}{\langle 0|P(t)P(0)|0\rangle} \tag{21}$$

where $A_4(t)$ is the 4-th component of an axial vector current; $A_\mu(t) = \bar{\Psi}(t)\gamma_\mu\gamma_5\Psi(0)$ and $P(t)$ is a pseudo scalar current; $P(t) = \bar{\Psi}(t)\gamma_5\Psi(0)$. Generally the renormalization constants for the axial vector current Z_A and for the pseudo scalar current Z_P are not unity for finite lattice spacing [29]. However we approximated Z_P/Z_A by unity because its value including non-perturbative effects is not known.

Fig. 5 and Fig. 6 show the hadron masses versus the quark mass defined by Eq.(21). We observe the linear behaviors

$$m_\pi^2 = A_1 m_q + A_0, \tag{22}$$
$$m_{\rho,p,\Delta} = B_{\rho,p,\Delta} m_q + m^c_{\rho,p,\Delta} \tag{23}$$

for $SU(3)$, abelian, monopole and (matter)×(monopole) [1]. m^c is the mass at the chiral limit defined by zero quark mass. The masses at the chiral limit after the abelian projection are slightly smaller than those of $SU(3)$.

C. Gross features of hadron masses

Fig. 7 and Fig. 8 show dimensionless ratios $m_\rho/\sqrt{\sigma}$ and $m_p/\sqrt{\sigma}$ versus m_π^2/σ where σ is the string tension in each gauge field. We can see that all ratios of the three types, in the abelian, the monopole and the (matter)×(monopole) gauge fields, are equal or very close to the values of $SU(3)$. In Fig. 7 and Fig. 8, long dashed lines represent the linear fits with m_π^2:

[1] The r.h.s. of Eq.(21) is almost proportional to m_π^2 because of Lorentz covariance [30].

$$m_{\rho,p,\Delta}/\sqrt{\sigma} = C_{\rho,p,\Delta} m_\pi^2/\sigma + \bar{m}^c_{\rho,p,\Delta}/\sqrt{\sigma}. \tag{24}$$

Now we use the fit (23) or the fit (24) for extrapolation toward the chiral limit. The masses normalized by the squared root of the string tension and $\chi^2/d.o.f$ of the fits are listed in Table III and Table IV. The masses of ρ, p and Δ are given by setting $m_q = 0$ for the fit (23) or $m_\pi^2 = 0$ for the fit (24). The two fits give almost the same results, $m^c_{\rho,p,\Delta}$ and $\bar{m}^c_{\rho,p,\Delta}$. This is consistent with smallness of A_0 in (22) as shown in Table III. Hence we call them as hadron masses in the following. We observe *abelian dominance* and *monopole dominance* for the hadron masses normalized by the squared root of the string tension

$$\frac{m_\rho^{SU(3)}}{\sqrt{\sigma^{SU(3)}}} \simeq \frac{m_\rho^{\rm abel}}{\sqrt{\sigma^{\rm abel}}} \simeq \frac{m_\rho^{\rm mono}}{\sqrt{\sigma^{\rm mono}}} \simeq \frac{m_\rho^{\rm (matt)\times(mono)}}{\sqrt{\sigma^{\rm (matt)\times(mono)}}} \tag{25}$$

$$\frac{m_B^{SU(3)}}{\sqrt{\sigma^{SU(3)}}} \simeq \frac{m_B^{\rm abel}}{\sqrt{\sigma^{\rm abel}}} \lesssim \frac{m_B^{\rm (matt)\times(mono)}}{\sqrt{\sigma^{\rm (matt)\times(mono)}}} \lesssim \frac{m_B^{\rm mono}}{\sqrt{\sigma^{\rm mono}}} \tag{26}$$

where B denotes p and Δ.

The ratios $m_p/\sqrt{\sigma}$ and $m_\Delta/\sqrt{\sigma}$ in the (matter)×(monopole) and monopole gauge fields are slightly larger than those of $SU(3)$. Comparing Fig.7 and Fig.8, the tendency is clearer in the data on $16^3 \times 32$ lattice at $\beta = 5.7$. Thus, the deviation may be due to the difference of the short range structure of the gauge fields. We have also found similar behaviors by measuring ρ or the baryon masses at different βs on the same lattice size. As β becomes smaller, the abelian and monopole dominances become more conspicuous.

We have plotted the quark mass versus $1/\kappa$ in Fig. 9. We see that $(1/2\kappa - 1/2\kappa_c)$ is not perfectly proportional to the quark mass derived by Eq.(21) in the abelian and the monopole gauge fields. We need some higher order terms such as $O((1/\kappa)^2)$. This shows that $(1/2\kappa - 1/2\kappa_c)$ cannot be recognized straightforwardly as the quark mass in the abelian and the monopole gauge fields. However in the case of $SU(3)$, the fits using (19), (23) and (24) give almost the same value of the masses for ρ, p and Δ (Table III and Table IV).

D. Hadron spectra in gauge fields without monopoles

Next, we investigate hadron spectra in the absence of monopoles. Hadronic correlators are measured in the monopoleless abelian field, i.e. in the photon part u^{Ph} and also in the monopoleless $SU(3)$ gauge fields Cu^{Ph}. The latter is (matter)×(abelian part)/(monopole part) = (matter)×(photon part).

Fig. 10 shows the masses of π and ρ versus $1/\kappa$ in the photon, the (matter)×(photon) and the free fields. The estimated masses of π, ρ, p and Δ in each field are listed in Table V.

As seen from Fig. 10 and Table V, the photon contribution does not produce any dynamical mass generation ($\kappa_c = 0.140(2)$ for $16^3 \times 32$ lattice, $\beta = 5.7$), namely,

$$m_\pi \simeq m_\rho, \quad m_p \simeq m_\Delta. \tag{27}$$

The mass ratio is given by

$$m_p/m_\rho \sim m_\Delta/m_\rho \sim 3/2 \tag{28}$$

in the case of the photon. The hadron masses are simply in proportion to the number of the bare quarks. The behavior is similar to those in the free case, although $\kappa_c = 0.125$.

Similar behaviors are seen in the monopoleless $SU(3)$ gauge fields. It does not either generate the mass gap ($\kappa_c = 0.157(2)$) as in the previous photon case. We find that *the dynamical mass generation cannot be produced without monopoles.* The matter field is not crucial for the dynamical mass generation.

IV. SUMMARY AND REMARKS

The hadron spectra in abelian, monopole, photon, (matter)×(monopole) and (matter)×(photon) fields are studied. The following results are obtained:

- The PCAC relation holds good in the abelian, the monopole and the (matter) × (monopole) fields. The squared pion mass is well proportional to the quark mass derived from the axial Ward identity. The perturbative or empirical relation $m_q \sim 1/2\kappa - 1/2\kappa_c$, does not hold in the abelian and the monopole gauge fields.

- The ratios of the hadron mass to the square root of the string tension of the abelian, the monopole and the (matter) × (monopole) are similar to those of $SU(3)$. In this sense, we have found the abelian dominance and the monopole dominance for the hadron spectra. However, some indications of the difference which may be interpreted as the shorter range effects are also found.

- No sizable dynamical mass generation is seen in the measurements both in the abelian and in $SU(3)$ gauge fields without monopoles. These results suggest that monopoles are crucial for the dynamical mass generation and that the photon part and the matter part are not important.

The data are consistent with the results of simulations in quenched $SU(2)$ QCD with Kogut-Susskind fermions [23].

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TABLES

		$SU(3)$:			abelian:			monopole:		
$L_s^3 \times L_t$	β	a[fm]	aL_s[fm]	#	a[fm]	aL_s[fm]	#	a[fm]	aL_s[fm]	#
$24^3 \times 48$	6.0				.101(1)	2.42(2)	52	.083(1)	1.98(2)	52
$16^3 \times 32$	5.7	.227(8)	3.63(13)	32	.189(2)	3.02(4)	150	.158(1)	2.52(1)	100
$16^3 \times 32$	5.8	.207(9)	3.31(14)	48	.154(3)	2.47(4)	78	.120(1)	1.91(1)	48
$12^3 \times 24$	5.4	.350(13)	4.20(16)	60	.318(7)	3.82(8)	110	.297(16)	3.56(19)	110
$12^3 \times 24$	5.53				.271(1)	3.25(2)	70			
$12^3 \times 24$	5.6				.235(2)	2.82(2)	100	.205(1)	2.46(1)	110
$12^3 \times 24$	5.66	.254(5)	3.05(6)	48	.210(3)	2.52(3)	102	.175(1)	2.10(1)	102

TABLE I. Physical lattice size (from the $SU(3)$, abelian and monopole string tension for $\sigma^{1/2}$ =440MeV) and the number of configurations on each of the lattice.

$SU(3)$:					
κ	m_q	m_π	m_ρ	m_p	m_Δ
0.150	.2422(166)	1.069(04)	1.118(05)	1.870(08)	1.911(09)
0.155	.0980(067)	0.888(03)	0.956(12)	1.344(09)	1.436(10)
0.160	.0380(026)	0.692(07)	0.814(10)	1.072(13)	1.215(18)
	.000	0.180(07)	0.605(08)	0.936(27)	1.092(18)
abelian:					
κ	m_q	m_π	m_ρ	m_p	m_Δ
0.150	.0660(53)	0.543(03)	.624(05)	1.049(11)	1.111(13)
0.155	.0307(25)	0.415(04)	.535(06)	.912(14)	1.001(18)
0.1575	.0200(17)	0.354(03)	.501(08)	.874(19)	.959(29)
0.160	.0035(13)	0.293(04)	.468(12)	.853(33)	.892(52)
	.000	0.267(05)	.456(08)	.821(24)	.888(43)
monopole:					
κ	m_q	m_π	m_ρ	m_p	m_Δ
0.135	.0970(57)	.633(03)	.678(32)	1.14(15)	1.18(17)
0.140	.0473(29)	.499(03)	.574(34)	.99(17)	1.04(21)
0.1425	.0311(20)	.440(04)	.535(39)	.94(21)	1.00(26)
0.145	.0216(13)	.379(04)	.495(50)	.89(24)	.98(35)
	.000	.281(11)	.452(10)	.83(17)	.92(19)

TABLE II. The quark mass and hadron masses for $16^3 \times 32$ at $\beta = 5.7$.

fit using m_q^{WI} for $12^3 \times 24$ at $\beta = 5.4$					
	SU(3)	$SU(3)(1/\kappa)$	abelian	monopole	(matter)×(monopole)
A_0	.110(1)	$---$	.123(2)	.139(5)	.123(4)
$\chi^2/d.o.f.$	.001	1.819	.020	.097	.042
$m_\rho/\sqrt{\sigma}$	1.09(06)	1.02(08)	1.07(03)	1.09(03)	1.15(01)
$\chi^2/d.o.f.$	.081	.990	.121	.397	.065
$m_p/\sqrt{\sigma}$	1.97(12)	1.83(18)	2.00(07)	2.09(05)	2.03(02)
$\chi^2/d.o.f.$	.278	1.950	.202	.167	.010
$m_\Delta/\sqrt{\sigma}$	2.17(11)	2.07(14)	2.12(08)	2.45(04)	2.07(07)
$\chi^2/d.o.f.$	.049	.210	.342	.027	.710

fit using m_q^{WI} for $16^3 \times 32$ at $\beta = 5.7$					
	$SU(3)$	$SU(3)(1/\kappa)$	abelian	monopole	(matter)×(monopole)
A_0	.032(2)	$---$	.071(3)	.079(6)	.047(2)
$\chi^2/d.o.f.$	.010	2.242	1.078	.790	.015
$m_\rho/\sqrt{\sigma}$	1.20(06)	1.15(08)	1.08(03)	1.29(03)	1.31(02)
$\chi^2/d.o.f.$	.041	.022	.661	1.475	.023
$m_p/\sqrt{\sigma}$	1.85(12)	1.74(18)	1.95(08)	2.37(06)	2.12(04)
$\chi^2/d.o.f.$	.377	1.04	5.824	.742	.025
$m_\Delta/\sqrt{\sigma}$	2.16(12)	2.08(14)	2.11(13)	2.63(06)	2.31(05)
$\chi^2/d.o.f.$	.106	.020	.373	.331	.037

TABLE III. The pion intercept and the ratios between the masses at the chiral limit and the squared root of the string tension. $SU(3)(1/\kappa)$ denotes the masses that given by fits as linear function of $1/\kappa$.

fit using $m_\pi^2/\sqrt{\sigma}$ for $12^3 \times 24$ at $\beta = 5.4$					
	$SU(3)$	$SU(3)(1/\kappa)$	abelian	monopole	(matter)×(monopole)
$m_\rho/\sqrt{\sigma}$	1.04(12)	1.02(08)	1.01(06)	1.00(04)	1.08(04)
$\chi^2/d.o.f.$	.043	.99	.051	.651	.010
$m_p/\sqrt{\sigma}$	1.88(23)	1.83(18)	1.90(12)	1.96(14)	1.91(16)
$\chi^2/d.o.f.$	.137	1.95	.081	.353	.108
$m_\Delta/\sqrt{\sigma}$	2.10(21)	2.07(14)	2.02(13)	2.36(17)	1.94(18)
$\chi^2/d.o.f.$	.024	.21	.117	.382	1.084

fit using $m_\pi^2/\sqrt{\sigma}$ for $16^3 \times 32$ at $\beta = 5.7$					
	$SU(3)$	$SU(3)(1/\kappa)$	abelian	monopole	(matter)×(monopole)
$m_\rho/\sqrt{\sigma}$	1.16(10)	1.15(08)	.99(05)	1.13(04)	1.23(05)
$\chi^2/d.o.f.$	.037	.022	.248	.208	.214
$m_p/\sqrt{\sigma}$	1.78(19)	1.74(18)	1.73(10)	2.14(12)	1.99(19)
$\chi^2/d.o.f.$	.216	1.04	.520	.099	.028
$m_\Delta/\sqrt{\sigma}$	2.10(19)	2.08(14)	2.01(14)	2.43(15)	2.19(19)
$\chi^2/d.o.f.$	.068	.020	8.413	2.993	.114

TABLE IV. The ratios between the masses at the chiral limit and the squared root of the string tension. $SU(3)(1/\kappa)$ denotes the masses that given by fits as linear function of $1/\kappa$.

photon:				
κ	m_π	m_ρ	m_p	m_Δ
.1150	1.379(2)	1.374(2)	2.182(4)	2.181(4)
.1200	1.120(2)	1.115(2)	1.790(4)	1.789(4)
.1250	.841(2)	.839(2)	1.355(4)	1.355(4)
.1300	.534(2)	.543(2)	.872(4)	.875(4)
.140(2)(κ_c)	0.0	.023(10)	0.033(16)	0.042(12)
(matter)×(photon)				
κ	m_π	m_ρ	m_p	m_Δ
0.130	1.380(2)	1.375(3)	2.192(6)	2.193(6)
0.140	.903(2)	.898(2)	1.451(5)	1.450(5)
0.145	.634(2)	.636(2)	1.023(4)	1.024(5)
0.150	.340(1)	.360(2)	.578(4)	.588(4)
free:				
κ	m_π	m_ρ	m_p	m_Δ
0.10	1.576(21)	1.581(18)	2.500(42)	2.502(41)
0.11	.982(25)	.997(16)	1.615(36)	1.620(34)
0.115	.636(25)	.663(13)	1.097(26)	1.105(24)
0.1225	.103(12)	.130(12)	.394(38)	.403(37)
0.1240	.023(03)	.031(04)	.264(26)	.266(26)

TABLE V. Hadron masses in the photon and the (matter)×(monopole) fields on $16^3 \times 32$ at $\beta = 5.7$ and in the free fields.

FIGURES

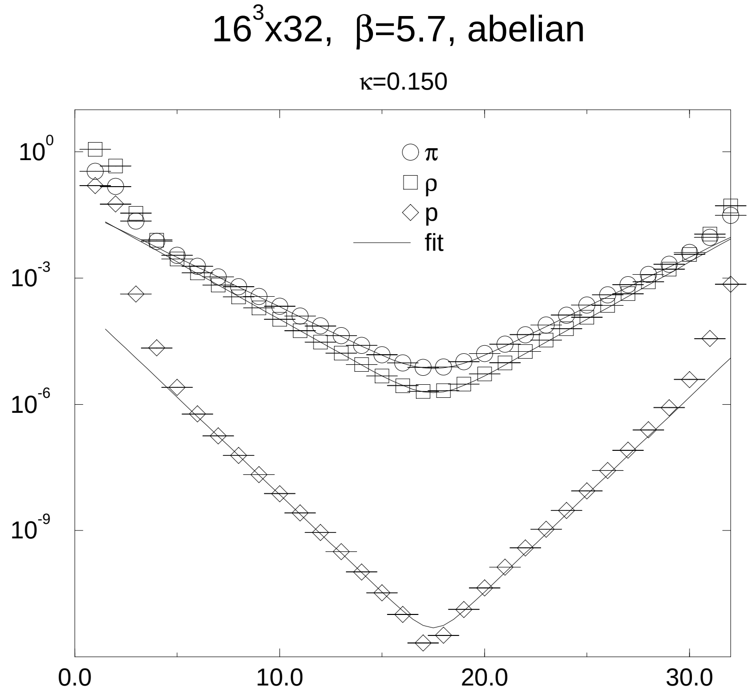

FIG. 1. Hadron propagators in the abelian gauge fields for $\kappa = 0.150$ at $\beta = 5.7$.

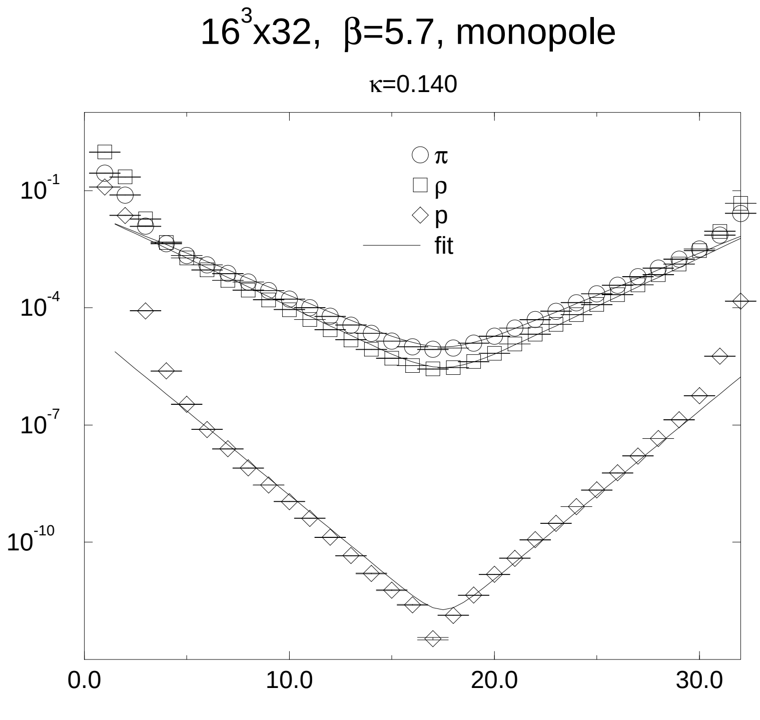

FIG. 2. Hadron propagators in the monopole gauge fields for $\kappa = 0.140$ at $\beta = 5.7$.

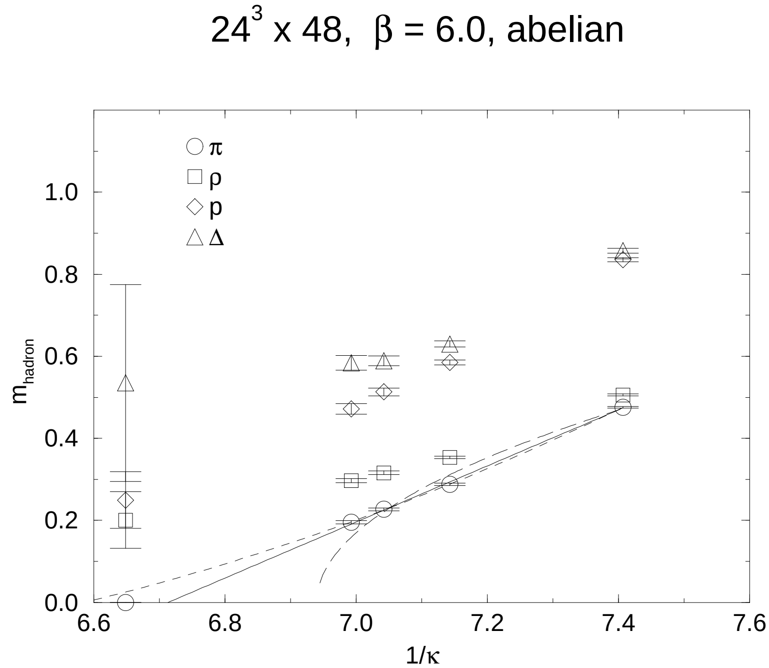

FIG. 3. The masses of π, ρ, p,and Δ versus $1/\kappa$ on $24^3 \times 48$ lattice at $\beta = 6.0$ in the abelian gauge fields.

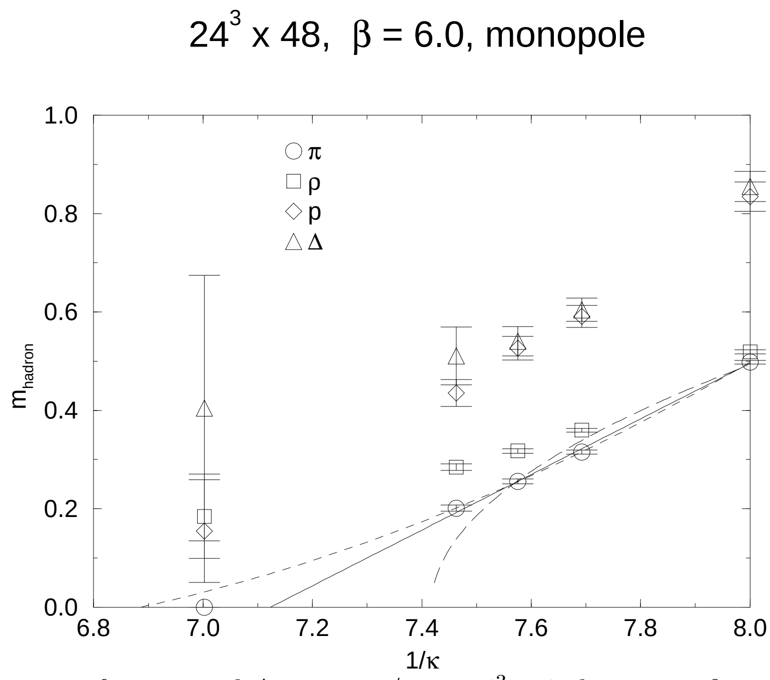

FIG. 4. The masses of π, ρ, p,and Δ versus $1/\kappa$ on $24^3 \times 48$ lattice at $\beta = 6.0$ in the monopole gauge fields.

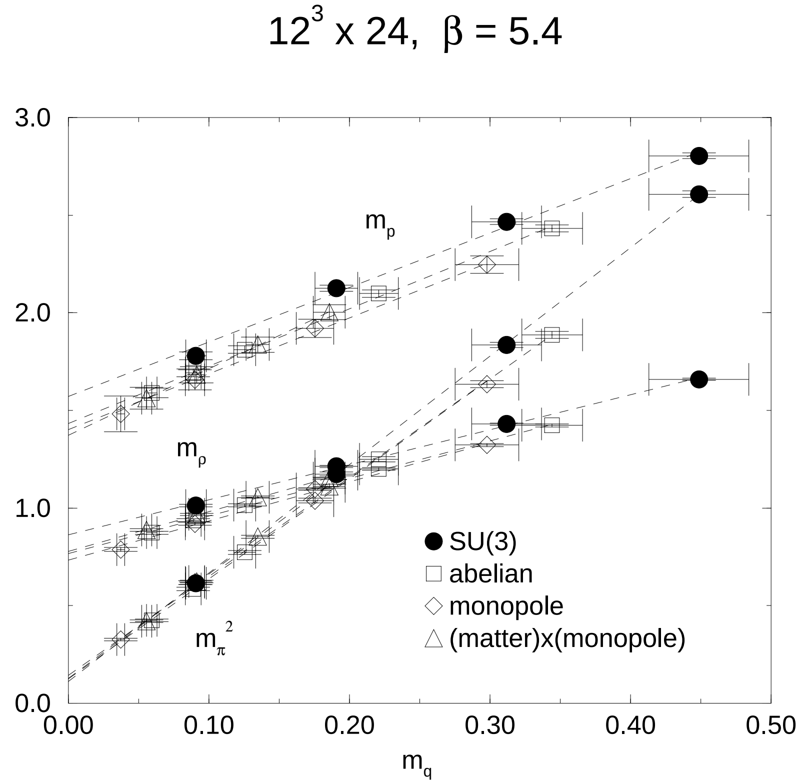

FIG. 5. m_π^2, ρ and p versus m_q.

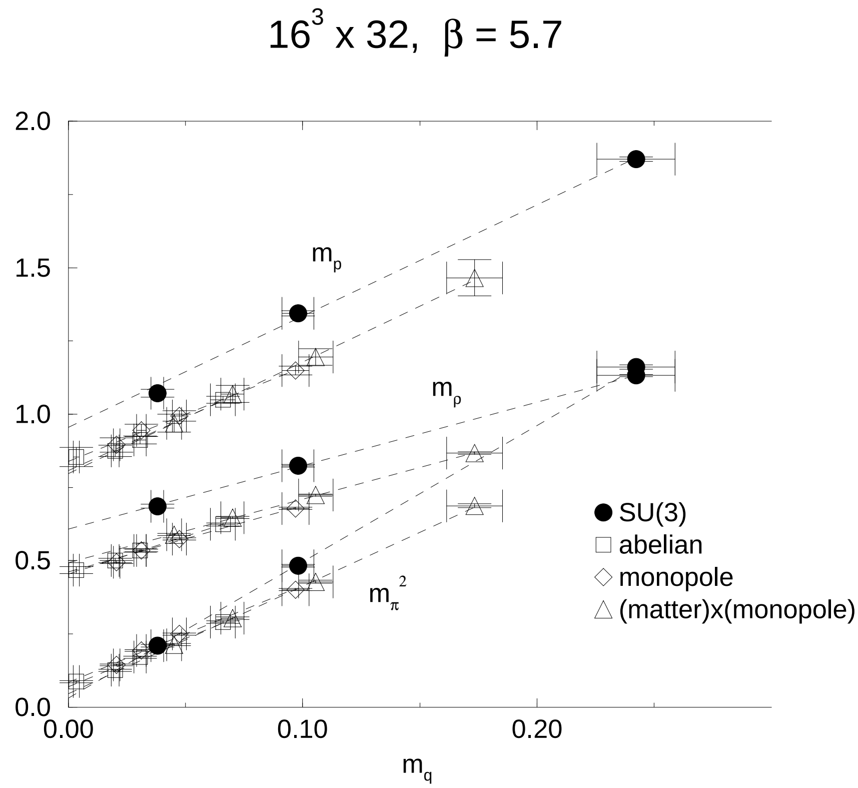

FIG. 6. m_π^2, ρ and p versus m_q.

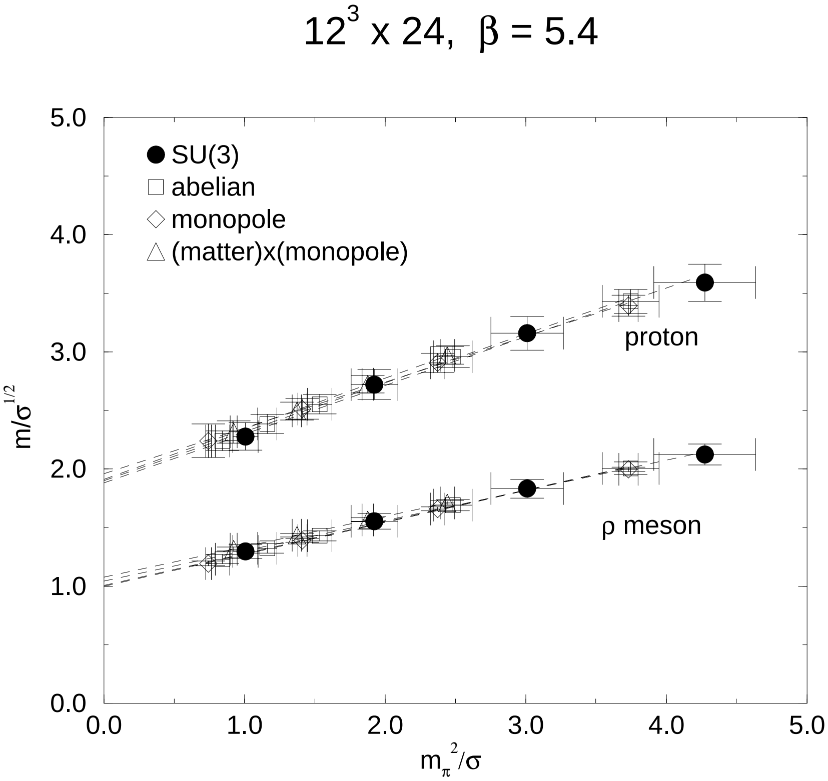

FIG. 7. The $m_\rho/\sigma^{1/2}$ and $m_p/\sigma^{1/2}$ versus m_π^2/σ.

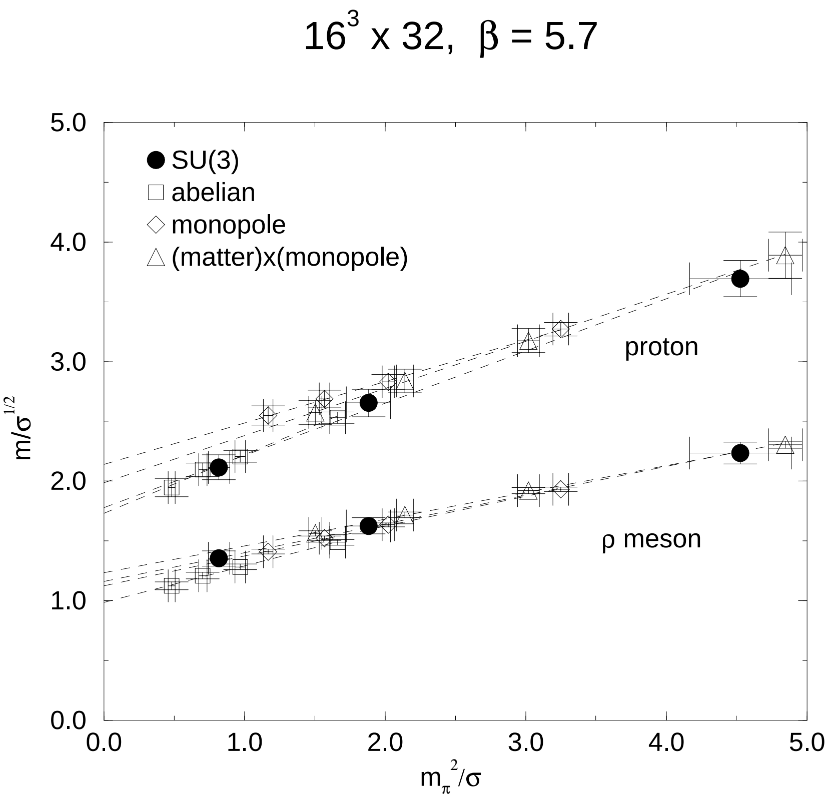

FIG. 8. The $m_\rho/\sigma^{1/2}$ and $m_p/\sigma^{1/2}$ versus m_π^2/σ.

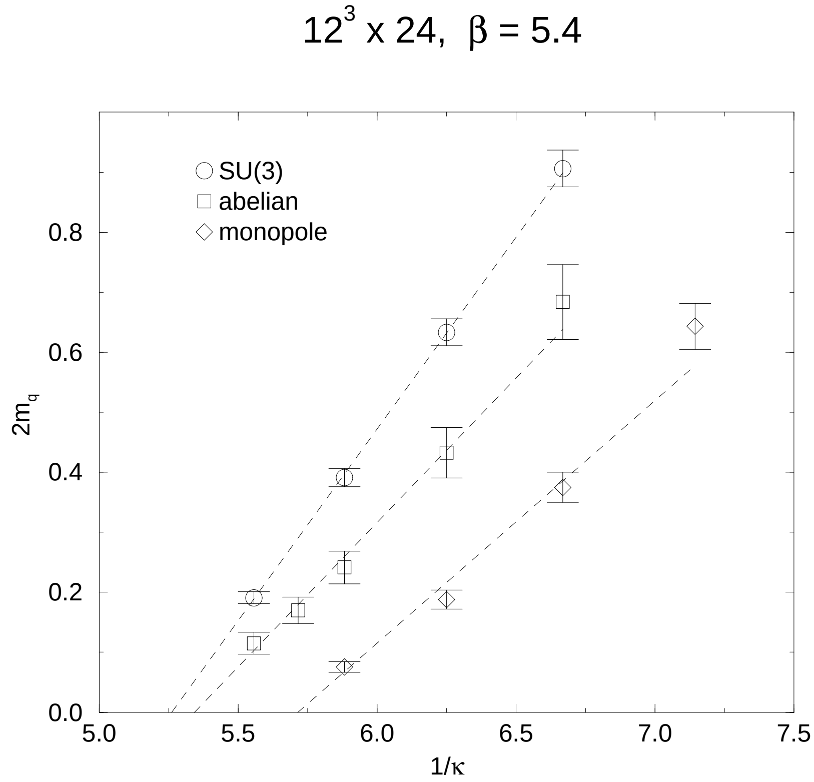

FIG. 9. $2m_q$ versus $1/\kappa$.

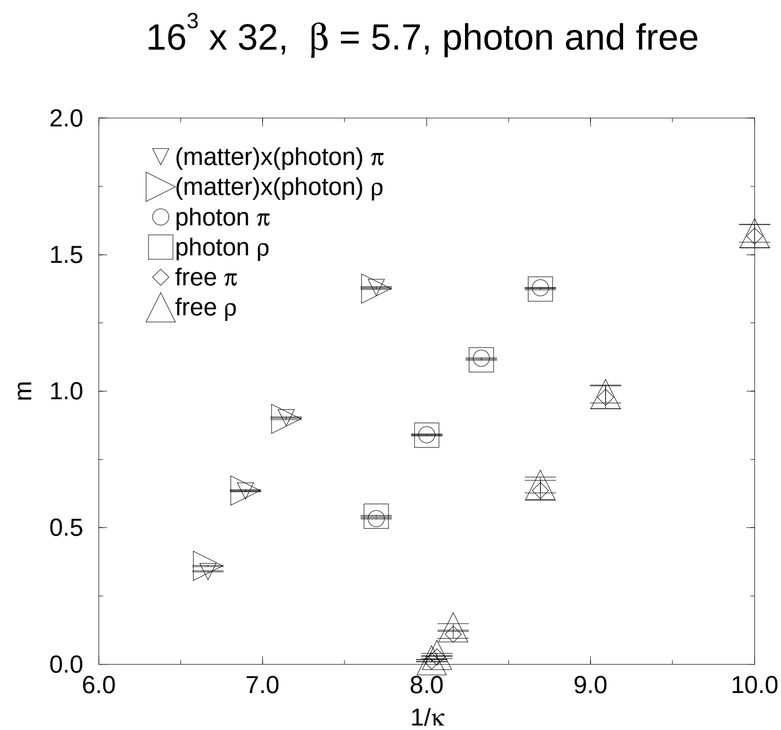

FIG. 10. The squared masses of π and ρ versus $1/\kappa$ in the free, the photon and the (matter)$\times$(photon) gauge fields.